Grassland degradation in China: Methods of monitoring, management and restoration

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Abstract

Grasslands in China cover nearly 4 million km^2, more than 40% of its total land area. Grasslands play an important role in livestock farming and environmental conservation. In spite of numerous efforts that have been undertaken to arrest land desertification in China, grassland degradation is advancing over wide areas through overgrazing, cropland misuse and unregulated collection of fuel and medical plants. This review presents specific examination of the present situation of grassland desertification in China, and discusses mechanisms of grassland degradation. Assessments of desertification since the 1980s are introduced, and its expanse and extent are discussed. Many scientists admit that both are causes, but two contradicting arguments surround the main cause of desertification, with one citing natural origins such as climate change, and the other pointing to anthropogenic factors such as overgrazing. Trials for clarifying mechanisms of grassland degradation are attempted from the perspective of water and energy dynamics. In addition, causes and measures of moving sand dunes and sandstorms are also discussed. For elucidation of the mechanisms of grassland degradation, the grassland ecosystem functions must be considered. Among the proposals, a mathematical approach and measurement of spectral reflectance are some new methods that are effective for assessing those functions. Measurements of soil respiration under altered grazing intensities are also useful to examine prospects in the event of global climate change. Several technologies for grassland diagnosis have been developed to arrest grassland deterioration. Indicator plant species have been determined according to grassland types. Relations of grazing pressure and species distribution have been quantified. Several measures for restoration of degraded grasslands are proposed as the next step of development in this field, including agro-ecological measures. A promising tool for grassland monitoring is the use of remote sensing in conjunction with geographic information systems. Accurate and real-time monitoring and management of grasslands have become increasingly feasible through sensor improvement in satellite and geographic information systems generalization in recent years.

Introduction

Lepers *et al.* (2005) presented a synthesis of known information about areas undergoing rapid land-cover change around the world over the past two decades, based on data compiled from remote sensing and censuses, as well as on expert opinion. Asia currently has the greatest concentration of areas showing rapid land-cover change, particularly dry land degradation. Grasslands in China cover 2.86 million km^2 (Zhu *et al.* 1985), or 3.98 million km^2 according to Ren (1995). On those lands, more than 100 million livestock are being raised. Xu, the Director-General for the Science and Technology Agency of Inner Mongolia Autonomous Region, expressed that desertification area in China has reached 27.3% of

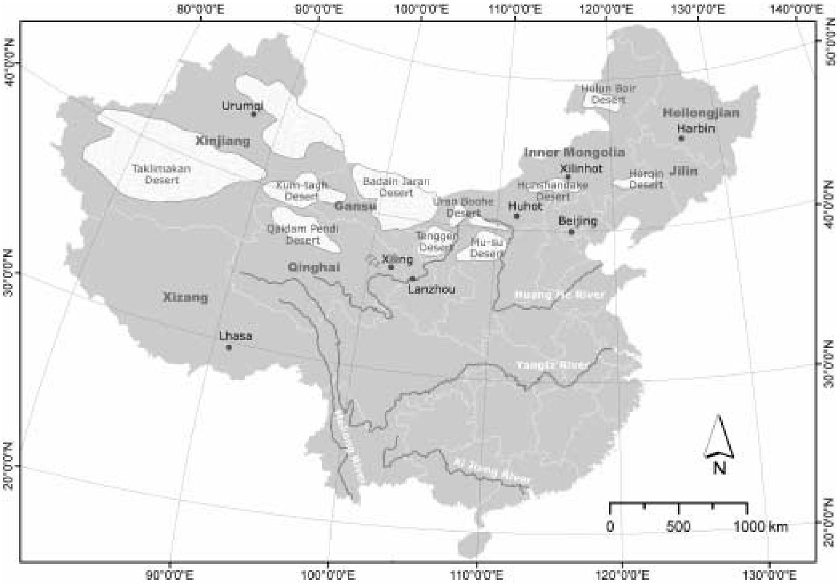

Figure 1 Locations of study areas mentioned in this paper, with main desert regions and cities in China.

national land area, and it is increasing by 2460 km^2 per year: 400 million people are likely to be affected and the direct economic loss is estimated as 54 billion yuan per year.

In this review paper, we comprehensively introduce examination of grassland degradation in China. It includes the present situation, causes, effects and desertification countermeasures. Sections include and overview, mechanisms of grassland degradation, function of grassland ecosystem, grassland diagnosis, grassland restoration and improvement, and grassland management using geospatial technology.

Names of regions and districts appearing in this paper are presented in Figure 1. (NB. Note 1: Chinese local names are sometimes described differently by authors; e.g. Horqin, Korqin, Keerqin, and Kerchin are inferred by the author to refer to the same area. *Leymus chinensis* has been called *A. chinense.* Therefore, in this paper, two different descriptions appear for one species. Here, we particularly emphasized the description by the original author.)

Overview

Li (1962) first systematized Inner Mongolia's vegetation types and their ecological distribution. Afterward, zonal vegetation of natural grasslands in China was clarified by Zhu (1988). The vegetation forms a broad belt from the plains of the north-east to the Tibetan plateau in the south-west; the vegetation is within a latitudinal range of 35°–50°N. Later, detailed and comprehensive information about grasslands in China was given by Ren (1995) and Liao and Jia (1996). Several key projects that examined control of grassland degradation and developing grassland production systems on various grassland types were launched by the Chinese national government (Nan 2005). Causes for grassland degradation have been asserted by many researchers, such as overgrazing by animals, incorrect agricultural management, collection of wood for fuel and herbs for medicine, and destruction by rodents. Although some aspects have improved, degradation continues to expand and intensify throughout the country. Yang *et al.* (2005) overviewed desertification assessments on both national and local levels. Here, they indicated two major problems facing the assessment of degradation: (i) the uncertainty of baseline assessments and indicator systems; and (ii) the misuse of remotely sensed data sources. Many articles about grassland degradation in China and its restoration have been published since the 1990s, but most have been written in Chinese. Kawanabe *et al.* (1998b) reviewed information on the grassland desertification during the recent 40–50 years in regions of north-eastern China and Inner Mongolia. They referred to 40 reports, most of which are written in Chinese. According to their report, areas of degraded grassland accounted for one-third of total area. Above-ground biomass had decreased from 2.2 to 3.0 t ha^{-1} in the 1950s to 0.70–0.90 t ha^{-1} in the 1990s. The article concluded that degradation was caused mainly by salinization and/or alkalization of soil and by sand drifting. In addition, they presented some practical countermeasures against desertification.

Grassland degradation is advancing also in alpine grasslands. Zhou *et al.* (2006) reviewed the situation of alpine meadows in the source region of the Yangtze and Yellow Rivers. Results of field investigations show that they estimated that there is approximately 357 × 10^4 ha (34% the entire study area) degraded grassland in the area; heavily degraded grasslands cover 74 × 10^4 ha (21% of degraded grassland). Based on those results, the principal factors causing grassland

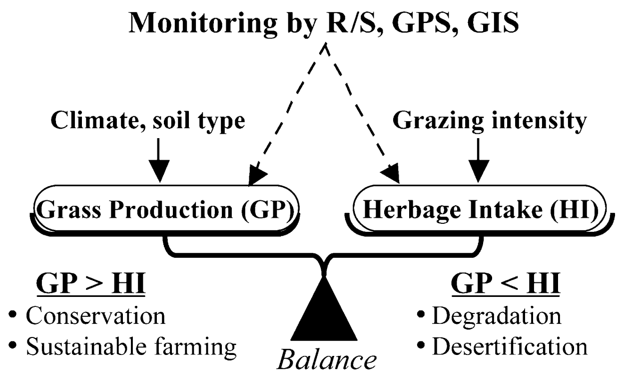

Figure 2 Concept of a real-time steppe monitoring system using satellite remote sensing, geographic information systems (GIS) and global positioning systems (GPS).

degradation are thought to be long-term overgrazing and the destruction by rodents that follows climate warming, which exacerbates grassland degradation.

The People's Republic of Mongolia (Outer Mongolia) is an area that is potentially affected by climate change, although the present situation of grassland in Outer Mongolia is not well known. Wuyunna and Okamoto (2006) reported changes in terms of agriculture and stock raising, ecosystems, and ecodynamics study in Mongolia.

How then can we grasp the present and future states of grasslands? Grassland conditions are determined by a balance of grass production (GP) and herbage intake by animals (HI). When HI is higher than GP, grasslands will be degraded. However, if the GP is greater than the HI, grasslands will be conserved and the land will recover (Figure 2). Akiyama *et al.* (2005) proposed a system to measure the GP and HI rates for predicting grassland conditions. The GP is determined by climate, soil, plants species and so on, whereas HI depends on the grazing intensity including the stocking rate, animal species, palatability, and so on. This system is intended for real-time monitoring of GP and HI using satellite data, geographic information systems (GIS), global positioning systems (GPS) and mathematical models.

Mechanisms of grassland degradation

Causes of degradation

Natural or anthropogenic cause?

Although research efforts addressing recent changes of desertification have increased, little is known about historical vegetation cover, soils, and past bio-geographic patterns. Wang *et al.* (2006) evaluated some key contributions to desertification or rehabilitation around the Otindag Desert in north China. The evaluation, which pertains to the period from the 1950s to the 2000s, includes an analysis of proxies for human activity, and variations in climatic indices. As a result, they concluded that previous studies might have overestimated the impact of human activities on environmental change. At the same desert, however, Zheng *et al.* (2006) obtained opposite results using different methods. In the experiment, a meta-process model was developed to simulate several key parameters of plant community and their dynamics over the past 40 years were analyzed. From the results of the simulation, they concluded that climate might not be the key cause for desertification in this land. Indeed, socioeconomic factors are mainly responsible for the changes.

The semiarid area in the northern China is an agro-pastoral transition zone. The environment there is sensitive to climate variation, particularly to precipitation. Gong *et al.* (2004) analyzed daily precipitation records of 30-gauge stations during May–September 1956–2000. The precipitation amounts showed only slightly decreasing trends, but some aspects of rainfall characteristics displayed great changes, such as the number of rainy days reduced, while light rain (< 10 mm day^{-1}) increased. Similar results were obtained by Harazono *et al.* (1993). Furthermore, Begzsuren *et al.* (2004) investigated how drought and dzuds (severe winter weather) affect livestock mortality in a non-equilibrium steppe ecosystem of Mongolia. Overall, unlike hot dry regions, livestock mortality in the cold dry regions is affected more by dzuds than by droughts. Dzuds can be frequent events, occurring as often as once every 2–3 years within a decade.

Energy balance

Several experiments have been conducted to clarify desertification according to water and energy dynamics among the atmosphere, vegetation, and soil in semiarid and arid zones. Zhao *et al.* (2004a) estimated the monthly potential evapotranspiration (PET) rate in the Zuli River Basin, western China. The Hargreaves model appears to be the best way to estimate PET in this district. The general methods described here are expected to be applicable to the entire Loess Plateau. Furthermore, Ma *et al.* (2004) measured some distributions such as regional land surface variables, vegetation variables and land surface heat flux over heterogeneous desertification regarding arid areas of north-west China; they analyzed it using a parameterized method of combining satellite remote sensing with field observations. Their results showed a reasonable regional distribution of surface reflectance, surface temperature, modified soil adjusted vegetation index (MSAVI, Qi *et al.* 1994), vegetation coverage and net radiation.

To elucidate desertification mechanisms, Li *et al.* (2000) conducted a grazing experiment in the Naiman sandy rangeland of Inner Mongolia. The experimental field included four plots in which grazing sheep numbers differed.

Micrometeorological data were analyzed using the Bowen ratio energy balance method. Their results suggest that albedo is an important indicator of potential grassland desertification. In addition, ratios of net radiation or the net available radiation to the solar radiation tended to decrease with increasing grazing intensity.

Soil and soil compositions

Xiao *et al.* (2006) proposed a novel index for detecting topsoil grain size composition using spectral reflectance measurements *in situ* and the soil physical analyses in the laboratory. The grain size composition of topsoil characterizes the soil texture and other physical properties. Coarsening of topsoil grain size (from clay and silt to sand) is a readily apparent indicator of land degradation; consequently, a change in the topsoil grain size is useful to monitor desertification using remotely sensed data. The proposed topsoil grain size index (GSI), which has a positive correlation with the sand content, was then applied to a Landsat TM image of 1993 and ETM+ image of 2000 to detect desertification process throughout the Siziwang Banner region of Inner Mongolia. At the Qinghai–Tibet plateau, Li *et al.* (2006) carried out a field survey to test the hypotheses on a regional scale using four field sites. Results indicated that the proportion of silt decreased from 12% in the initial stage to 1% in the very severe stage, clay decreased from 71% in the initial stage, to 42% in the very severe stage, and sand increased from 17% in the initial stage to 93% in the very severe stage. Soil water-retention capacity and soil organic matter are also reduced with desert development. In response to changes in soil properties, vegetation undergoes change in terms of species composition, species diversity, coverage, structure and life-forms.

A grazing experiment was conducted in Naiman during 1992–1996 to elucidate desertification processes (Zhao *et al.* 2005). Results of this study indicate that some small bare spots appeared on the ground and later merged into larger bare areas in the rangeland. The total bare area reached 52% and the average depth of wind erosion was 25 cm in the fifth year of the study. Their salient conclusion was that sandy rangeland with wind-erodible soil is susceptible to desertification.

Land-use changes

Hao and Wu (2006) analyzed relations of land-use types and their conversions on desertification based on multitemporal Landsat TM images acquired in 1985 and 2000 in the Mu Us sandy land. Both cultivated land and forest lands are more affected by desertification development than rangeland. Namely, the conversion from forest land to cultivated land can accelerate the development of desertification while the opposite conversion decelerates the developing process. That study revealed that improper land use conversion might hasten desertification.

Evolution of sandstorms and fixation of sand dunes

Evolution of sandstorms

Monitoring sandstorm evolution is an important task that is necessary to understand the Chinese environment. Wang *et al.* (2004b) overviewed dust storms in China. Most dust storms originate from the Hexi corridor and the western Inner Mongolia Plateau, the Taklimakan Desert, and the central Inner Mongolia Plateau. Dust most likely originates from deteriorated grasslands, Gobi, alluvial, lacustrine sediments, and wadis at the outer edges of deserts. It was reported that dust storms became less frequent in most regions of China during 1950–2000 despite increases in some regions. The dust storms are highly correlated with human activities and climate changes. Several new indices were devised for monitoring sandstorm evolution. Jin and Yan (2004) derived a sandstorm index (SI) and a desert index (DI) from a radiative transfer equation using multichannel microwave measurements with DMSP SSM/I data in northern China. Wang *et al.* (2004a) investigated flux and composition of wind-eroded dust generated from five landscape types in the inland basin of the Heihe River of north-western China using an aeolian dust sampler. The dried terminal lakebed (dried-up lakes in lower reaches) sand of the degraded grasslands contributed to production of the greatest quantity of aeolian dust. The chemical composition of dust differed according to the location of sampling within the Heihe Basin. Protecting grasslands in the lower reaches of the Heihe River Basin from degradation and rehabilitating the dried-up terminal lake would do much to reduce aeolian losses in the region.

The sand transportation rate and wind speed were measured concurrently to assess the variation of the sand transportation rate in Horqin sandy land at different levels of desertification (Li *et al.* 2003). Some surface properties (e.g. plant height, vegetation cover, and surface soil hardness) were also measured. The rates increased linearly from the least desertified fixed sandy land to severely desertified mobile sandy land on both measurement dates. The rates decreased with plant height by an exponential or power function. Differences in sand transportation rates among the four sandy lands were largely attributed to differences in their surface properties, such as vegetation cover and soil surface hardness. In addition, Li *et al.* (2005) monitored the daily wind erosion rate at degraded grasslands over an erosive period. The daily wind erosion rate in the fixed sandy land was only approximately one-fifth in the semifixed sandy land, 1/14 in the semi-shifting sandy land and 1/47 in the shifting sandy land, suggesting a much higher resistance of the fixed sandy land to wind erosion than at other sites.

Stabilizing a moving sand dune

Several measures have been proposed for stabilizing moving sand dunes in the Horqin sandy land. Zhang *et al.* (2004) conducted an experiment to compare effects of different measures for stabilizing sand dunes on vegetation restoration. The measures included: (i) building corn-stalk fencing; (ii) placing a wheat straw checkerboard; and (iii) planting *Artemisia halodendron* on the dunes. Both placing wheat straw checkerboard and planting *A. halodendron* yielded the best results and are therefore considered to be the most promising techniques for the restoration of vegetation in this area.

Nemoto and Lu (1992) considered an effective method to use vegetation for stabilizing moving sand dunes. *Agriophyllum squarrosum*, an ephemeral plant in shifting sand dunes, was examined. Typically, *A. squarrosum* is able to invade as a pioneer because of the elongation of its fine roots, which are well adapted to dry sandy soil and which are able to penetrate to deep soil layers containing moisture. According to the same concept, Nemoto *et al.* (1997) examined the growth of crops and invading weeds at six sites under different cultivation conditions in the Korqin sandy land in Naiman district. Sand dune reactivation has been controlled by weed invasion.

Function of grassland ecosystem

Statistical methods for grassland evaluation

Shiyomi *et al.* (2002) proposed a grassland evaluation method based on the beta-binominal distribution. Wang *et al.* (2002b) applied it in the North-west Heilongjiang steppes. It was adopted to describe the frequency of occurrence and spatial heterogeneity for each plant species. Results indicated that, under degraded conditions, species diversity decreased and the spatial heterogeneity of the communities tended to increase. Huang *et al.* (2004) applied a beta-binominal distribution method for classification of macro-vegetation. They divided a vegetation map of Inner Mongolia into 1122 quadrats to analyze vegetative spatial heterogeneity and ecological characteristics. The vegetation comprised coniferous and broadleaf deciduous forest, shrub, grassland and desert on an east-to-west gradient. Based on the weighted average heterogeneity and Shannon-Wiener's diversity index, in all, 99 types of Inner Mongolia's macro-vegetation were characterized.

Spectral reflectance analysis for vegetation survey

Recent progress in remote sensing technologies permits accurate and timely monitoring of grassland conditions (Akiyama and Kawamura 2003a). Such information includes individual plant information *in situ* and identification of landscape units over wide areas.

Hyperspectral reflectance

Reflectance of soil and vegetation reveals grassland conditions. Hyperspectral reflectance data were used to extract wavelength peaks of different grass species (Yamano *et al.* 2003). *Caragana microphylla*, which is an indicator plant of dry lands, was detected among the four dominant grass species found in the typical Xilinhot grassland using fourth-derivative peaks around 670 nm and 720 nm. A radiative transfer simulation showed that derivative spectroscopy of hyperspectral reflectance data by vegetation can be an effective tool for advanced mapping and for grassland monitoring.

Satellite images

The following two reports describe methods to evaluate the grass coverage in conjunction with *in situ* spectroscopic data and satellite images taken of areas near Lake Qinghai in western China. Liu *et al.* (2004) assessed the severity of grassland degradation from the grass coverage ratio and the proportion of unpalatable grasses (PUG) collected over 1 m^2 sampling plots. Ten vegetation indices were derived from Landsat TM bands 3 and 4, and from the *in situ* spectral reflectance data. Regression analyses were used to produce normalized difference vegetation index (NDVI, Rouse *et al.* 1973) and soil adjusted vegetation index (SAVI, Huete 1988), which are the most reliable indicators of grass coverage and PUG among satellite-derived vegetation indices. Through establishment of regression models, the TM image was converted into maps of grass coverage parameters. These maps were merged to form a degradation map at an accuracy of 91.7%. In addition, Zha *et al.* (2003) proposed a reflectance-based method to estimate grass coverage. The *in situ*-measured percentage of grass cover was sampled from 1 m^2 plots at 68 sites. The NDVI was derived from both surface spectral reflectance *in situ* and radiometrically calibrated Landsat TM bands 3 and 4. After standardization of the latter with the former, the TM-derived NDVI exhibited a close relationship with the *in situ* measured samples ($R^2 = 0.74$). This relationship confirmed the usefulness of quantifying grass coverage from satellite images with an overall accuracy of 89%.

Wuyunna *et al.* (2002) conducted an analytical study to produce a distribution map of the landscape in the Inner Mongolia grasslands using satellite images acquired in 1978 and 1992. They identified landscape units such as developed vegetation, degraded stands and croplands, and surveyed floristic composition of the plant communities in the landscape unit. Those results suggest that fragmentation occurred in the stand of *L. chinensis* and *Stipa grandis*, which are developed grasslands. The total area of developed grasslands decreased, although the *Artemisia frigida* community stands increased their territories, which indicated degradation of the grasslands.

Soil-plant-animal relations

Grassland ecosystems consist of soil, plants and animals. It is important to clarify ecosystem functions, which are affected by all three of those elements, quantitatively.

Soil and plants

To determine the potential productivity of native climax vegetation, Okamoto *et al.* (2000a) investigated the above-ground biomass, its seasonal dynamics and vegetative composition protected by a fence and an unmown *Stipa baicalensis* community of the Songnen plain of north-eastern China. Results indicated that the maximum above-ground live biomass of the community was 222.8 gDM m^{-2} at 130 days after starting growth. The estimated crop growth rate reached its maximum (3.9 gDM m^{-2} day^{-1}) at 66 days after starting growth. Okamoto *et al.* (2001) examined patchily distributed vegetation and the soil environment in the steppes of north-eastern China to study the relation between vegetation type and soil properties on a microstand level. The study area (10 m × 10 m) was divided into 100 subsites (1 m × 1 m). Vegetation factors (i.e. coverage, number of species and diversity index H′) of the divisions were found to relate negatively with their surface soil factors (i.e. pH and electric conductivity of soil). The spatial distribution of the vegetation types was affected primarily by the degree of saline-alkalization in the surface soil.

Structures of macropores in the soil layer are important as an indicator of water-retention and drainage. Sato (1992) examined the chestnut soil of the Inner Mongolia semi-desert. It was studied three-dimensionally by examining the physical condition of the soil, along with the morphology of macropores using X-ray and contrast media. Tubular root pores, which originate from grass roots, play an important role in macropore formation in grassland soil.

Soil microbial biomass, number and activity

Studies of microorganisms in grassland started in the 1990s but most of them were published in symposium proceedings and did not appear in journals.

Liao *et al.* (1990) examined biomass of soil microorganisms under different grassland communities in Xilingol steppe. They reported that the microorganisms biomass was approximately 400 g in *L. chinensis–S. grandis* grassland, 450 g in *Filifolium sibiricum* grassland, 650 g in meadow steppe, but 300 g for sandy land. Yang *et al.* (1991a) analyzed nutrition dynamics after scarification and fertilization on *L. chinensis* grassland. Scarification with fertilization plot increased microbial biomass.

Li and Zhang (1994) investigated the seasonal variation of bacteria in Kerchin rangelands. The number of ammonia bacteria maximized in October but was seldom found in other months. It was high especially in the soil layers between 30 and 70 cm depth. The number of the denitrifying physiological group showed different pattern depending on the depth of soil. At the surface layer (0–10 cm) it increased in winter, in the 10–30-cm layer it is high in summer, while in the 30–70-cm layer, it was at its maximum in September.

Yang *et al.* (1991b) examined seasonal variation of the soil microorganisms decomposition rate on *L. chinensis* grassland in north-eastern China. The decomposition rate showed high correlation with soil temperature and soil moisture content. Liao and Zhao (1994) studied soil microorganisms and their activities in the range of Inner Mongolia. Biomass and enzyme activities were examined among four types of steppe. They found that biomass was high in meadow steppe and typical steppe, and enzyme activity was highest in typical steppe, followed by meadow steppe, steppe-desert and desert-steppe.

Guan and Du (1994) isolated two N-fixing bacteria of wild rye plant in Xilingol steppe. They are *Klebsiella axytoca* and *Klebsiella pneumoniae* ssp. *Preumoniae.* N-fixers were found for the first time in arid grassland in Inner Mongolia.

Plants and animals

The role of small mammals in grasslands has been examined in several studies. Wang *et al.* (2003) studied the role of soil moisture contents and vegetation structure in the spatial distribution of small mammal species in the typical steppes of Inner Mongolia. Linear regression analysis revealed that soil moisture contents and the number of small mammal species are inversely related. In addition, Hongo *et al.* (1993) investigated damage of mound construction on grasslands by Cansu mole-rats in the shrub-steppe vegetation in the Loess Plateau. They destroyed the vegetation and soil structure. The damage area was estimated to be as much as 15% of the total area of the northern slope.

Studies of grazing yaks remain inadequate; there is a shortage of knowledge on the subject. A University of Miyazaki group undertook collaborative work with the Yushu Prefectural Animal Husbandry and Veterinary Station for a study of grazing yaks in the Eastern Tibetan High Plateau. Song *et al.* (2003; 2004) investigated Selenium (Se) and vitamin E concentrations in the blood of grazing yaks and rangeland plants; chronic shortages were evident in those districts. Activities of Se and vitamin E are closely related. Shortages of these nutrients delay growth and foster several physiological diseases.

Carbon dynamics in grassland ecosystems

During the past two decades, carbon sequestration of terrestrial ecosystems has become an important scientific issue related to global warming. The contribution of grassland ecosystems has received more attention recently because of its large area, high active carbon turnover rate and fragile property to disturbance. Reportedly, 25% of all carbon in the terrestrial biome is stored in grassland ecosystems.

Soil respiration

Grazing intensity might alter the soil respiration rate in grassland ecosystems. Cao *et al*. (2004) measured the soil respiration rate under two different grazing intensities (high-intensity grazing, HG 5.35; low-intensity grazing, LG 2.55 sheep ha^{-1}) in an alpine meadow on the Tibetan plateau. The measurements showed that CO_2 efflux was almost twice as high at the LG site as at the HG site during the growing season. Estimates of net ecosystem CO_2 exchange at the LG site were 2040 g CO_2 m^{-2} y^{-1} to the atmosphere, which was approximately one-third more than the 1530 g CO_2 m^2 y^{-1} released at the HG site. Hirota *et al.* (2005) investigated carbon flux in the same area; CO_2 and methane fluxes were 5.6-fold to 11.3-fold higher, respectively, under grazing conditions than under nongrazing conditions.

Carbon storage in grassland

Carbon sequestration in grassland ecosystems is influenced strongly by both anthropogenic activities, such as grazing management and cultivation, and global changes. To investigate the effects of anthropogenic activities on carbon sequestration in grassland, Wang and Cui (2006) conducted a series of experiments in grassland ecosystems of the Xilin River Basin. They found that soil organic carbon (SOC) stored in meadow steppes was affected strongly by the conversion of grasslands to croplands, decreasing the former by 35–38%, although no marked change of SOC was apparent after 22 years of grazing in *L. chinensis* dominated grasslands.

In a country-scale analysis of China, Ni (2002) estimated carbon storage in all grasslands of China by the carbon density method and based on a nationwide grassland resource survey. Chinese grasslands were classified into 18 types. Carbon densities in vegetation and soils and utilizable areas, and the low, median and high values of carbon in vegetation, soils and total carbon storage for each grassland type are calculated. Based on median estimates, vegetation, soil and total carbon storage of grasslands in China were 3.06, 41.03 and 44.09 Pg C, respectively. China's grasslands make up only 6–8% of all the world's grassland area but have 9–16% of the total carbon of the world's grasslands.

Nitrogen flow

Chen and Huang (1990) studied nitrogen flow in *Aneurolepidium chinensis* grassland in Xilingol, Inner Mongolia. They investigated seasonal movement of nitrogen in plant parts, species and soil layers. Nitrogen storage in above-ground parts was 1.19, 3.50 and 4.25 g m^{-2} in spring, summer and autumn, respectively. Nitrogen storage in below-ground parts was 5.44 g m^{-2} in spring, but attained 9.21 g m^{-2} during autumn.

Grassland diagnosis

Indicator species of grassland degradation

Species list of grassland

For conducting field surveys *in situ*, identifying the names of plant species poses a barrier. Okamoto *et al.* (2000b) introduced the main growing species in north-east China, including two districts in the Heilongjian Province, three regions in the Hulunbeir, and one region in the Xilingol of Inner Mongolia. In that list, 46 families and 294 species were included using scientific names, Chinese names (in Chinese characters with pronunciation) and Japanese names. The list is extremely convenient, especially for foreign researchers who will start field experiments in these regions.

Steppe grasslands are spreading throughout the Ukraine. Kawada *et al.* (2006) surveyed the floristic composition of plant communities, species diversity of stands, and above-ground biomass in steppe grasslands in the vicinity of Khakiv, Ukraine which are dominated by stands of *Stipa capillata* L., *Medicago romanica*, *Poa angustifolia* and *Inula ensifolia*. There are 37–46 species that constitute 195–380 g above-ground biomass in 1 m^2 quadrats. The species diversities are 2.98 and 2.66 for the *S. capillata* and *M. romanica* stands, respectively. Floristic composition in Kharkiv was different from that of Inner Mongolia, though the genus of plants was similar. Cheng and Nakamura (2006) performed a phytosociological study on steppe vegetation in the vicinity of Kharkiv. Species distribution usually reflects the soil water condition.

Alkali-tolerant species

Aneurolepidium chinense (L. chinensis) has two ecotypes: a gray type and a green type. Kawanabe *et al.* (1996a) found that the gray one is more tolerant of saline and drought conditions and grows on more alkaline and drier soil than the green one. It was ascertained that the habitats of the two ecotypes were clearly segregated from one another by the soil alkalinity.

Meadow steppes in the Wulanaodu region of Inner Mongolia have been severely degraded through overgrazing, soil alkalization and moving sand dunes. Kawanabe *et al.* (1994a) surveyed vegetation of cutting and grazing pastures to discover indicator species of soil alkalization. In severely degraded pastures, higher frequencies were observed of bare ground, *Suaeda* type and *Chloris* type, but *Arundinella* type and *Agropyron* type were found in weakly degraded or non-degraded pastures. Furthermore, some indicator species of non-degraded and degraded pastures were given attention not only for their species, but also on the life forms and growth form in Keerqin sandland (Kawanabe *et al.* 1998a).

Soil water and climate gradient

The distribution and the abundance of desert plant communities were examined by Zhang *et al.* (2005b) in the lower reaches of the Tarim River in south Xinjiang. Most investigated species had a low frequency of occurrence. Correspondence analysis revealed a separation of growth forms into three distinct groups corresponding to different ground-water levels: < 3 m, 3–5 m and > 5 m.

Ecological variance of a large amount of steppe species along the climate gradient was examined by Li (1996). The relationships in the vegetation environments were analyzed quantitatively based on a field survey at 119 sites along an itinerary from the desert-steppe transition zone to that of the forest-steppe in the Inner Mongolia steppe region. The preponderances of 30 factors in determination of vegetation composition were put into a hierarchy according to their sampling quality and their mutual information with the 50 most frequent species. The results showed that the climate was preponderant, whereas the topographic and managerial factors were either secondary or localized.

Relation of grazing pressure and species diversity

Species diversity

Some researchers have studied changes of species diversity under grazing influence. On the Xilingol steppes, Li (1993) investigated the species diversity of two representative grazing gradients. The results showed that the species richness of the two communities was reduced with increased grazing intensity, whereas their indices of evenness and diversity on moderately grazed sites were higher than those on both non-grazed and heavily grazed sites. In the same area, Wuyunna *et al.* (1999) examined the species diversity and the above-ground biomass. As a result, the rank of constituent species changed according to varying grazing pressure. *A. chinense* decreased its importance value, and *A. frigida* raised that value. The species diversity index (H′) exhibited the maximum value in the intermediately grazed stand for each community. In the Horqin sandy land, Zhang *et al.* (2005a) examined the patterns and dynamics of species diversity along a chronosequence of vegetation recovery on the sand dunes to assess the probability of vegetation recovery via succession. The species richness and diversity indices increased gradually with succession. Results showed that restoration via succession holds promise for vegetation recovery and desertification control within protected, fenced enclosures. In the Heilongjiang Province, Tsutsumi *et al.* (2003) investigated plant species' diversity according to three grasslands with different degrees of grazing intensity (heavy, intermediate and light). Grassland plant species' diversity and spatial heterogeneity were estimated for each species according to the frequency of occurrence of each plant species. Results suggested that the species diversity decreased and the spatial heterogeneity of species diversity increased with increasing grazing pressure on the grasslands.

Supplying drinking water for grazing animals is a limiting factor for raising them in arid areas. Settlements were usually developed around water wells or openings of pipelines. Therefore, it is known that the distance from spring has a negative correlation with grazing intensity. Sasaki *et al.* (2006) investigated floristic composition in Bulgan, South Gobi, People's Republic of Mongolia along a transect from spring and grouped them into five vegetation types using TWINSPAN. The DCA axis 1 arranged all quadrats in order of grazing intensity; the floristic composition changed dramatically in a lopsided stepwise-pattern along this axis. The patterns of floristic composition were determined by grazing intensity together with palatability, which was the dominant environmental effect at the site.

Indices for grassland conditions

Nakamura *et al.* (1998) proposed an importance value to discuss grassland conditions with changes of floristic composition under different grazing pressures. The species alternation in the stands was surveyed in the Xilingol steppe by setting up experimental fields with varying numbers of sheep. The importance value of type I species, such as *A. chinense* decrease with increased grazing pressure. For type II, with species such as *Potentilla acaulis*, an increase was apparent with increasing grazing pressure. Type III, including *Chenopodium aristatum* L., appeared in heavily grazed stands. Type IV species such as *Kochia prosrata* L. Schrad were unaffected by grazing pressure. From these results, an abundance of type II species indicates grassland degradation; and the presence of type IV species indicates that the stand is in danger of desertification. Expanding such a conception, Nakamura *et al.* (2000) developed the stand quality index (SQI), which was devised based on the volume of indicator species in the stand, which reflected grassland quality. Using the SQI, Yiruhan *et al.* (2001) evaluated changes in floristic composition of grassland according to grazing intensity. It was well reflected with the status of degradation in the Xilin River Basin.

For a landscape-scale analysis based on GIS, Tong *et al.* (2004) investigated steppe degradation in the Xilin River Basin. In this process, they developed a steppe degradation index (SDI) that incorporates information about the spatial extent and severity of steppe degradation. Results showed that the total area of degraded steppe increased from 7191.3 km^2 in 1985 to 7689.3 km^2 in 1999.

Effects of overgrazing

Some grazing experiments were conducted at the Korqin (Horqin) sandy land in Inner Mongolia. Nemoto *et al.* (1994) defined the proper stocking intensity using sheep. Results showed that most species decreased with increased grazing intensity, but that of *Aristida adscensionis* was scarcely influenced by grazing pressure. Spiny and pioneer plants in shifting sand dunes were grazed. Ohkuro and Nemoto (1997) studied the process of vegetation and soil restoration by grazing control. They applied TWINSPAN for all samples to classify floristic data and canonical correspondence analysis (CCA) for samples of sand dunes to explore the relation between vegetation restoration and environmental variables including soil property and topography. Finally, they suggested that an ecological evaluation of carrying capacity for each land unit (e.g. landform unit) is necessary to maintain sustainable land use of sandy grasslands in semiarid regions. Zhao *et al.* (2004c) carried out grazing experiments for 5 years of grasslands that had been overgrazed for many years. Plant species diversity, plant biomass, soil properties and sheep live weight were examined. Sheep live-weight gain (individual, kg ha^{-1}) decreased markedly in the final 3 years of the experiment in the overgrazing treatment (six sheep). Total weight gain (kg ha^{-1}) was the highest in the moderate treatment (four sheep). The proper grazing intensity should be two to three sheep or sheep equivalents per hectare for this area.

Su *et al.* (2005) examined characteristics of vegetation and soil properties under continuous grazing and exclusion of livestock for 5 and 10 years in representative degraded sandy grassland. Excluding livestock grazing enhances vegetation recovery, litter accumulation, and development of annual and perennial grasses. Soil organic carbon and total N concentrations, soil biological properties including some enzyme activities and basal soil respiration improved following a 10-year exclusion of livestock, suggesting that degradation of the grassland is being reversed.

Restoration and improvement of grasslands

Restoration of alkalized pasture

Alkali-tolerant species

Kawanabe and colleagues comprehensively examined the relationships between soil alkalization and vegetation under consequent grazing in north-eastern China. To clarify the present situation of vegetation and discover how its utilization might be harmonized with conservation practices, a vegetation survey was carried out for haymaking pasture, grazing pasture and protected pasture. Results indicated that *Suaeda glauca*, an alkali-soil tolerant species, dominated instead of *Aneurolepidium chinense* by heavy grazing (Kawanabe and Zhu 1991). That fact indicates a disturbance by heavy grazing if annual plants and alkali-tolerant species invade into degraded grazing pastures. Soil pH was 8.47–8.90 in grazing pastures, but it was 6.17–6.46 in cutting pastures. Physical and chemical properties of soil are severely devastated in grazing pastures. The bare soil and vegetation types were distributed corresponding with the microtopography (Kawanabe *et al.* 1993). The sequence of soil alkalinity of vegetation types is as follows: bare ground, *Suaeda* type, *Chloris* type, *Artemisia* type, *Puccinellia* type > *Aneurolepidium type* > *Arundinella* type. Soil alkalinity and overgrazing are the main causes of pasture degradation, suggesting that less-alkaline soil might improve degraded vegetation (Kawanabe *et al.* 1994b).

Restoration

Kawanabe *et al.* (1999a) reported that vegetation development coincides with soil fertility improvement; moreover, once-degraded pastures require a long time for recovery. Accumulation of soil organic matter and vegetation development are closely correlated. To diagnose stages of recovery from desertified grasslands, not only by the life form and the growth form of dominant species, but also the measurements of vegetation such as coverage, plant height, number of annual and perennial species, and existence of degradation indicator species and so forth are effective (Kawanabe *et al.* 1999b).

Kawanabe *et al.* (1996b) introduced various agro-ecological countermeasures against fixing moving sand dunes and for rehabilitation in the Keerqin sandy land. Surveying the process of recovering from the desertified pastures at the Keerqin sandy land, Kawanabe *et al.* (1998c) analyzed desertification effects on livestock management in villages of eastern Inner Mongolia.

Rehabilitation by agro-ecological measures

Water and nitrogen utilization

In China, tremendous efforts have been undertaken for rehabilitation of desertified land for productive use. Among them, the approach of Zhao *et al.* (2004b) is ameliorative: bio-drainage using different desert vegetation to control the high water tables and reverse observed salinity/solicity trends in the border area of the Manas Alluvial Fan. The groundwater table dropped in the summer of the fifth year, which was sufficient to prevent secondary salinization.

The two dominant species, *L. chinensis and S. grandis*, have different distribution areas in the Xilin River Basin: wetter and fertile for *L. chinensis*, and drier and infertile for *S. grandis*. Chen *et al.* (2005) measured the plant N content, C : N ratio, δ13C value and photosynthetic characteristics at five different rates of N-addition. They found that N addition engendered a considerable increase in N concentrations of plant tissues and a decreased in C : N ratio of the two species. However, the physiological response pattern such as photosynthesis and water-use efficiency (WUE) differed among species. These results suggest that *L. chinensis* achieved higher WUE at the expense of decreasing nitrogen use efficiency (NUE); in contrast, *S. grandis* simultaneously maintained higher WUE and NUE, which might partially explain the regional distribution of those two species in relation to the moisture and nutrient availability. Li *et al.* (2004) also carried out experiments to: (i) determine the effect of vegetative water utilization on soil water content; and (ii) to monitor the long-term vegetative response to the change of soil water content after establishing the revegetation of sand dunes in the Tengger Desert in northern China. It was concluded that water utilization of different plant species influences the spatial distribution of water inside the soil profile.

Soil properties

Shirato *et al.* (2004, 2005) evaluated the effects of restoration of sandy land using measures of afforestation and exclosure combined with sand-fixing measures from the changes in soil properties at a sandy grassland in northern China. In an enclosure experiment, they set fences enclosing two shifting sand dunes. In 1996, for each dune, they applied two measures, burying wheat straw in a checkered pattern (Sc) and planting seedlings of *A. halodendron* (Ar), a kind of sand-fixing shrub. The effectiveness was assessed for 6 years. A biological soil crust with high contents of SOC and fine particles formed within 3 years. The crust reduced wind erosion. The Sc technique was slightly more effective rather than Ar because Sc allowed invasion of various species. As for afforestation, changes in soil properties were examined near and within 3-, 9-, 19-year-old plantations of poplar. The contents of fine particles and SOC were higher at the windward edge than in the center of the 19-year-old plantation.

Rehabilitation of vegetation

Gao *et al.* (2001) evaluated the effectiveness of agro-ecological measures using multi-temporal aerial photographs in Yulin, Shaanxi Province of north-western China. The trend of desertification between 1960 and 1987 is modeled from changes in other land coverage. Results showed that desertified areas had decreased by 717.91 ha during the study period as a result of rehabilitation efforts. Planting of grass is the least effective measure for halting sand dune encroachment, whereas planting shrubs is the most effective.

Sugiura *et al.* (1998) evaluated the use of sheep dung as a water retention agent to establish a method for low input improvement of degraded grassland in semiarid area. Germination from dung pellets showed a good result when pellets were embedded 1 cm into the ground. The dung pellets were buried in the wetter soil; pellets were capable of absorbing approximately 2.2-fold their mass in water and retaining it for a few days.

Wind erosion has triggered dust and sandstorms. Wang *et al.* (2002a) assessed long-term effects of improved crop rotations and crop residue management practices on wind erosion in Wuchan County using the Environmental Policy Integrated Climate (EPIC) field-scale simulation model. The simulation indicates that preserving crop stalks until land is prepared by zone tillage for the next year's crop markedly reduces wind erosion, by 60%. Simultaneously, grain and potato yields were maintained or improved. Significant reduction in erosion, 35–46%, also resulted from delaying stalk removal until late January in the next year through to late April.

As a trial to increase yields, studies were conducted by Wang and Guo (1993) under conditions of pure sowing and sowing of a grass-legume mixture consisting of *L. chinensis* and *Hedysarum mongolicum*. The results suggest that the sowing of a grass-legume mixture with deep ploughing is most suitable for increasing dry matter production in the winter cold zone of China.

Effects of degradation on sustainable agriculture

In China, numerous factors have strongly affected rural life and have threatened agricultural sustainability. Zhao *et al.* (2006) conducted a field experiment on desertified cropland with gradients of wind erosion and accumulated sand to investigate changes in soil and crop growth properties resulting from desertification in the Horqin sandy land. Results indicated that the soil environment degraded significantly; crop growth and biomass were severely restrained by wind erosion. In badly eroded cropland, soil clay, SOC, total N and P, available N and P, and average soil moisture decreased, respectively, by 59.6%, 71.2%, 67.4%, 31.4%, 64.5%, 38.8% and 51.8%. In the windy and sandy region in Inner Mongolia, some measures to control cropland erosion should be introduced, including construction of wind-breaks, stubble cultivation, increased organic fertilizer and spring irrigation.

Until recently, some indicators have been developed for evaluating agricultural sustainability. For example, Komatsu *et al.* (2005) used a method that compares human carrying capacity (HCC), with the actual exploitation level of resources. Predicting the ratio of present population density to human carrying capacity (they call the rate of population accommodation) in 2010 implies two conclusions. First, rural life in the study area will be threatened by 2010 if the land conversion policy is continued and crop productivity does not increase. Second, the quality of life will be maintained in 2010 if an increase in crop productivity compensates for the decrease in economic productivity per unit land caused by the land conversion policy. Another approach applying fuzzy theory, developed by Wang *et al.* (2005), is a mathematical model to appraise natural grasslands of northern China. Three types of grassland were verified as examples, showing high accuracy of the method.

Establishing grassland protection areas (GPA) is regarded as an effective measure to protect grassland. He *et al.* (2005) presented a method to support the local government's effort in zoning of GPA. The method includes two major steps: (i) to extract seed points of candidate GPA using remote sensing techniques and GIS; and (ii) to simulate the zoning of GPA using a cellular automata model. It was evaluated using a case study in the Xilingol steppe. The results show that an integrated approach can rapidly identify the candidate GPA that satisfy the zoning requirement.

Grassland management using geospatial technologies

Application of remote sensing

Tueller (1989) anticipated the availability of remote sensing for rangeland resource development and management from the 1980s. He expected an increased number of professional range managers with expertise in remote sensing. For this training, he recommended the training of principles of aerial photograph interpretation, digital image analysis technology, increasing use of GIS, airborne video remote sensing, and the use of newly developed high-resolution systems. His evaluation was prescient. Responding to those needs, the Society of Rangeland Management held the "Remote Sensing/GIS Symposium for Rangeland Management" in 2000. Johnson (2001) edited summaries of the symposium. Full versions of these papers are available at http://uvalde.tamu.edu/jrm/remote/*index.htm*.

Anticipating the development of new technology, Akiyama *et al.* (2004b, 2005) proposed a new interdisciplinary science, called "remote sensing ecology". Development of satellite sensors can promote this stream. Recent years have ushered in remarkable improvements in spatial-, spectral-, and temporal resolution, which are representative of super-high-resolution satellites such as QuickBird and IKONOS, hyperspectral sensor on-boarding EO-1/Hyperion, and daily observation by Terra/MODIS. Those tools facilitate the combination of conventional processing methods on ecological experimentation *in situ* and satellite remote sensing techniques (Figure 3).

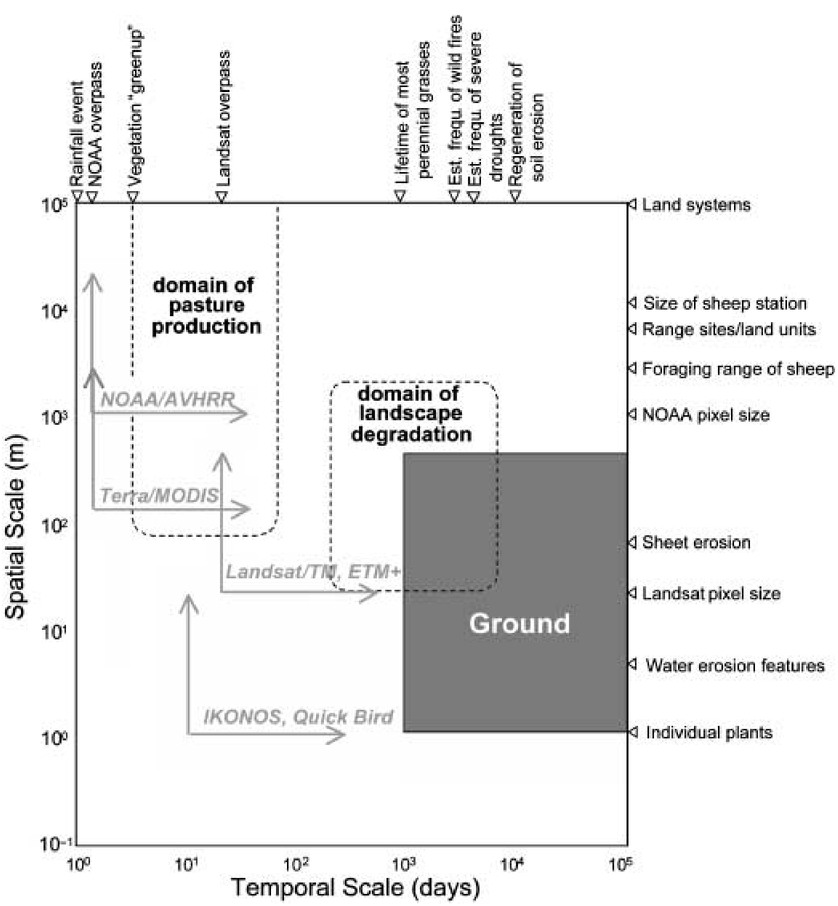

Figure 3 Temporal and spatial scales of the arid and semiarid rangelands with the capabilities of IKONOS, QuickBird, Landsat/TM, ETM+, Terra/MODIS, and NOAA/AVHRR systems with the domains of grass production and rangeland degradation overlain. (Akiyama and Kawamura 2003b modified the figure in the result of Graetz 1987.)

Table 1 General characteristic of NOAA/AVHRR, Terra/MODIS, Landsat/TM, ETM+ and DSMP/SSMI

Satellite	NOAA-16	Terra	Landsat-5	Landsat-7	DSMP-F13
Sensor name	AVHRR	MODIS	TM	ETM+	SSM/I
Sensor type	Optical	Optical	Optical	Optical	Microwave
Launch	21 September 2000	18 December 1999	1 May 1985	15 April 1999	24 March 1995
Orbit	843 km	705 km	705 km	705 km	844–856 km (min–max)
Swath width	2700 km	2330 km	185 km	185 km	1400 km
Number of bands	Five bands	36 bands	Seven	Eight	Seven
Repeat coverage	Daily	Daily	16	16	–
Spatial resolutions at nadir	1.1 km	250 m (bands 1–2) 500 m (bands 3–7) 1000 m (bands 8–36)	30 m (band 1–5,7) 60 m (band 6)	30 m (band 1–5,7) 60 m (band 6) 15 m (Pan)	43 km × 69 km (19.35 GHz) 50 km (22.235 GHz) 25 km (37.00 GHz) 13 km × 15 km (85.5 GHz)
Band width (μm)					
Band 1	0.58–0.68	0.620–0.670	0.45–0.52	0.45–0.52	19.35 GHz (HH)
Band 2	0.72–1.00	0.841–0.876	0.52–0.60	0.52–0.61	19.35 GHz (VV)
Band 3	A: 1.58–1.64, B: 3.55–3.93	0.459–0.479	0.63–0.69	0.63–0.69	22.235 GHz (VV)
Band 4	10.3–11.3	0.545–0.565	0.76–0.90	0.78–0.90	37.0 GHz (HH)
Band 5	11.5–12.5	1.230–1.250	1.55–1.75	1.55–1.75	37.0 GHz (VV)
Band 6		1.628–1.652	10.4–12.5	10.4–12.5	85.5 GHz (HH)
Band 7		2.105–2.155	2.08–2.35	2.09–2.35	85.5 GHz (VV)
Band 8		Omitted band 8–36		0.52–0.90	

These tools enable clarification of real-time monitoring of above-ground biomass and its quality in terms of leaf protein contents (Akiyama and Kawamura 2003b). For example, Li *et al*. (1998) estimated the above-ground biomass of four different types of vegetation in Fukang County, Xinjian using NOAA/AVHRR images. Kawamura *et al*. (2005d) also suggested advantages of satellite remote sensing as a tool for monitoring grassland ecosystems. Here, the advantages might be sufficient to observe wide areas, and to review data of past decades. In addition, integrated use with satellite data and GIS/GPS might allow detection of human pressure on grassland ecosystems, which was difficult using satellite data alone. Table 1 shows the name of satellites and specifications of sensors used in this review.

Remote sensing in conjunction with GIS and GPS

Monitoring of grazing animals

A powerful information technology system which stores, analyses and displays both spatial and non-spatial data, GIS is expanding rapidly with the growth of computer technology. Kawamura *et al*. (2003a, 2005a) developed a methodology, using Terra/MODIS-derived NDVI data combined with GPS data and GIS technology, for quantifying the effects of grazing intensities (GI) on plant productivity in the Xilingol steppe. To quantify the grazing pressure, a GI map of three herds of sheep was created using a grid cell method with tracking data captured by GPS. The relationship between GI and estimated plant biomass revealed a poor negative correlation. It indicates that plant biomass was reduced with increasing GI. When the plant biomass data were separated into two different vegetation types, marshy meadow and typical steppe, a stronger negative correlation was obtained between GI and biomass ($R^2 = 0.887$) in the typical steppe data. Effective methods for grassland management have been proposed, which combine recent developments of space technology with those in information technology (Akiyama and Kawamura 2004a). Advances in accuracy and portability of GPS sensors permit their versatile use in field surveys and research into animal behavior. Such a system might provide useful information about sustainable uses of grasslands to range managers.

Yearly changes of grassland

Regarding analysis of land cover and/or land use changes based on Landsat images, Imagawa *et al*. (1997) attempted to detect desertified areas using multi-temporal images, and developed a monitoring method in the Horqin desert area. Using three indices obtained using a Landsat TM band combination, they determined the yearly changes of desertified areas. Based on the GIS analysis, Zhang *et al*. (2003) investigated desertification of transitional zones of Desert Loess in the Yulin region from two Landsat TM images (1987 and 1999). Results showed that desertification is still severe and that the desertified land accounts for 67.7% of the total land area. The distribution of desertified land shows a marked spatial imbalance. This imbalance is related to the difference in physical factors and land-use patterns. The combined effects of those factors, along with other human activities, might engender development of desertification.

In the Xilingol steppe region of Inner Mongolia, Tsunekawa and Fukuhara (1990) compared the grassland biomass change between 1976 and 1985 over 80 km × 80 km of area. They found that above-ground biomass in most areas decreased dramatically; nevertheless, the study was not quantitative. Later, using Landsat images in almost the same area, Akiyama and Kawamura (2003a) analyzed land cover changes during 18 years from 1979–1997. Results showed that the areas of productive grassland had been decreasing, although the low-productivity over-grazed grasslands had increased. For larger scale analysis using NOAA/AVHRR-derived NDVI data, monthly NDVI images over northern China (500 km × 500 km) revealed seasonal and yearly fluctuations of grassland biomass on a regional scale. In addition, Kawamura *et al.* (2003b) developed a methodology for estimating wide area above-ground biomass from AVHRR-NDVI values in the Xilingol steppe region. Applying this method, the above-ground biomass in August 2003 was estimated as 1.17 t ha^{-1}. This result clarified that above-ground biomass decreased approximately 40% during 14 years in this district. In addition, seasonal changes of NDVI of NOAA were estimated using mean air temperature and the sum of precipitation in the previous period in Inner Mongolia. The results of calculations on seasonal NDVI revealed that the error between the observed NDVI value and the estimated one was 12.9% (Kawamura *et al.* 2004a).

Monitoring grass quality

NOAA/AVHRR and Terra/MODIS are both global monitoring satellites that can acquire the same region as a daily image. However, Terra/MODIS images, which are newer, have spatial resolution (250 m), which is far superior to that of NOAA/AVHRR (1100 m). Kawamura *et al.* (2005b) compared the capability of spectral vegetation indices (VI) derived from AVHRR and MODIS when estimating biomass, standing crude protein (CP) and CP concentrations in leaves. Regression analysis revealed that the MODIS-VI showed a good coefficient of determination (R^2 = 0.77–0.83) with regard to estimations of the total and live biomass. Furthermore, MODIS-EVI, which uses blue wavelength, was a good predictor of standing CP (R^2 = 0.74) compared to AVHRR (R^2 = 0.53). These results suggest that MODIS-VI can reliably detect the phenology and pasture quantity and quality of steppe grassland area. Kawamura *et al.* (2004b, 2005c) also conducted a study to determine the potential suitability of Terra/MODIS for monitoring short-term phenological changes in pasture conditions in a semiarid region. Applying the regression model, the EVI accounted for 80% of the variation in live biomass, 77% of the total biomass, 11% of the CP concentration and 74% of the standing CP. Applying these results, seasonal changes in live biomass and the standing CP can be described in the four selected sites with different degrees of grazing intensity.

Concluding remarks

Grasslands in China play an important role in livestock farming and environmental conservation. In spite of numerous efforts have been undertaken to arrest land desertification, grassland degradation is advancing over wide areas. Many collaboration works between Japan and China have started since the late 1980s. In this paper, we introduced an examination of grassland degradation in China. It included the present situation, causes, effects and desertification countermeasures.

Desertification is caused mainly through anthropogenic factors such as overgrazing, and additionally with natural origins such as climate change. Trials for clarifying mechanisms of grassland degradation were attempted. In addition, causes and countermeasures were also proposed. For elucidation of mechanisms of grassland degradation, the grassland ecosystem functions must be considered. Several technologies for grassland diagnosis have been developed to arrest grassland deterioration. Among the proposals, indicator plant species are effective for assessing the grassland conditions. Some new technologies such as a mathematical approach using models and measurement of reflectance were introduced. A promising tool for wide and heterogeneous grassland monitoring is the use of remote sensing in conjunction with GIS.

Grasslands in China play an important role for global carbon dynamics. To clarify mechanisms of grassland desertification, comprehensive study must be continued.

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